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Profs. Hermann Haus and Erich Ippen

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

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Interferometric Measurement with Squeezed Light
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Annual Report covering period
January 1, 1998 – December 31, 1998
and Retrospective over duration of Grant covering period
February 1, 1992 – December 31, 1998

Principal Investigators: Hermann A. Haus and Erich P. Ippen

Staff: Dr. F. X. Kärtner, post-doc
Dr. M. Margalit, post-doc
S. Namiki, visiting scientist
Dr. M. Shirasaki, visiting scientist

Students: K. Bergman, graduate student
L. Boivin, graduate student
J. K. Bounds, graduate student
P. Chou, graduate student
C. R. Doerr, graduate student
I. Lyubomirsky, graduate student
C. X. Yu, graduate student

Preface

This report covers the period from January 1, 1998 to December 31, 1998 and was prompted by a request from the front office for a Final Report. In view of the fact that our contract was renewed, and a final report was not really in order, we submit this report in full in lieu of the annual report, even though it contains coverage of work from 1992 to 1998. We thought that its contents give a useful overview of the work.

Goal of Research

Theoretical and experimental investigation of generation of squeezed light using the Kerr effect in fibers. Demonstration of improved sensitivity in interferometric measurement with squeezed light. Development of a theory of quantum optical measurement based on a full quantum mechanical description of the measurement apparatus.

Generation and Use of Squeezed Vacuum

In our work we concentrate mainly on the generation of squeezed vacuum, as opposed to amplitude squeezing. This focus on squeezed vacuum is motivated by the greater flexibility of its use. Squeezed vacuum is separated from the pump and can be phase shifted relative to the pump for either amplitude or phase fluctuation reduction in

interferometric measurements. The first generation of pulsed squeezed vacuum was accomplished by K. Bergman as part of her PhD thesis. The Guided Acoustic Wave Brillouin Scattering (GAWBS), first discovered by the IBM group at Almaden, restricts the spectral window within which the squeezed radiation can be observed and must be overcome if reliable broadband squeezing is to be achieved. There are three ways of suppressing GAWBS, all of which have been realized:

(a) Pump pulses are employed with a high repetition rate ($\geq 1\text{GHz}$). The GAWBS then occupies only a spectral band around the pulse repetition frequency, leaving the excitations outside this band free of GAWBS excitations.

(b) Two versions of a low repetition rate pump pulse are used, one delayed by less than 1 ns relative to the other and phase reversed with respect to it. The pump pulses see the same acoustic modulation state of the fiber, since GAWBS has constant amplitude over such a short time interval. In the balanced detection of bandwidth much less than 1 GHz the GAWBS picked up by the two pulses cancels.

(c) The squeezing is accomplished with pulses of high intensity such that squeezing is achieved in a short fiber (of the order of 1 m or less), rather than in a Sagnac loop that is typically 50 m long. The GAWBS evolves, at first, differently from the squeezed radiation. Thus if squeezing is accomplished in a short fiber, the GAWBS level can be kept low.

Schemes (a) and (b) have been tested successfully first[1,2]. The squeezing with the GHz pump achieved 5.1 dB of shot noise-reduction. In particular, the set-up using scheme (b) was expanded to include a measurement of phase in a Mach-Zehnder interferometer into which the squeezed vacuum was injected[2]. A measurement noise 3 dB below shot noise was demonstrated.

Both of these experiments were carried out with relatively long optical pulses at 1.3μm, a wavelength at which the fiber is dispersion-free. The squeezing by such pulses may be viewed as a succession of squeezing events in intervals of approximately constant pump intensity. The balanced detector integrates over such squeezing. Because of the different amount of squeezing by pump radiation of different intensities, the superposition of the different squeezed vacuum radiations results in a maximum shot noise reduction of 7 dB using a pulse of Gaussian profile. Hence if higher degrees of shot noise reduction are to be achieved one would need the pump to be a pulse of constant amplitude, or, more realistically, a soliton. Solitons on a dispersive fiber generate squeezed radiation associated with the entire pulse, rather than apportioned to segments of the pulse of different intensities. The 7 db limit on squeezing is removed.

Scheme (c) was implemented more recently with solitons using cross-phase modulation[3]. This scheme was proposed by L. Boivin and H.A. Haus in an Optics Letter[4]. In the experiment, 150 fs pulses were used in a 20 cm long fiber. The shot noise reduction was 3 dB. This is a scheme that shows great promise and its investigation is being continued.

Another means of squeezing has been analyzed thus far only theoretically. Squeezing depends on the nonlinear interaction of the pump with vacuum fluctuations. The larger the pump intensity, the stronger the squeezing. Hence, one would expect that squeezing generated internally in a *modelocked laser*, with a correspondingly larger intensity, could be a more effective way for the generation of squeezed vacuum. This question has been taken up in a theoretical paper that confronted a new issue. The field inside a modelocked laser undergoing squeezing is, by its nature, not a classical state as assumed in all previous models of squeezing. We analyzed this problem and found the possibility of generation of squeezed radiation in this novel way[5].

Quantum Jitter of Modelocked Lasers

The quantum analysis of solitons, necessary for an understanding of the generation of squeezed vacuum with solitons in a modelocked laser as outlined in the preceding section requires a quantum treatment of a modelocked laser. We took up the challenge and developed a quantum theory of noise of modelocked pulses. Pulses of soliton character have four degrees of freedom: amplitude, phase, timing and carrier frequency. The pulse width is tied to the amplitude by the so called area theorem. Noise, and in particular quantum noise, drives these four perturbations. Whereas unavoidable pump fluctuations drive amplitude fluctuations, the main cause of timing jitter is quantum noise (spontaneous emission). We have confirmed this fact by measurement of the timing jitter of passively modelocked fiber ring lasers. We found that the timing jitter (of the order of 1 ps with an integration time of 0.1 s) is fully attributable to the quantum noise[6,7,8]. In fact, it was found that the timing jitter of modelocked lasers is much smaller than the one achievable with programmed time delays in commercial sampling scopes

Direct Measurement of Self-phase Shift

We have devised a novel method to measure the nonlinear phase shift produced by the Kerr effect based on Spectral Interferometry (SI). SI measures the sum spectrum of a reference and a signal that are coherent and separated in time by τ. The beating between signal and reference generates a sinusoid in frequency whose period is the inverse of the temporal separation τ. We ensure that only the signal, not the reference, is affected by the fiber nonlinearity. So the nonlinear phase imposed on the signal distorts the signal-reference spectral interference. Near the center of the spectrum the distortion is manifested by a shift of the beat pattern, which is a direct measure of the phase shift at the peak wavelength. We have shown numerically that it approximates well the dynamic nonlinear phase shift at the temporal peak of the pulse.

We have implemented this technique in an experiment using 1.7 km of fiber. We tuned our optical source so that the fiber dispersion was negative or positive depending on the wavelength of the optical signal. We observed that for the positive dispersion case the spectrum broadens as the input power increases. The nonlinear phase shift also increases linearly with input power. For the negative dispersion case the spectrum narrows as the input power increases because of soliton effects. The nonlinear phase shift also increases initially. However, when the soliton condition is reached, both the spectral bandwidth and the nonlinear phase shift stay the same. This is because an increase of the input

power beyond the soliton limit generates continuum and does not contribute to the soliton energy. These experimental observations agree well with our theoretical calculations and numerical simulations. Figure 1 shows some of the experimental results. Figure 1a shows the optical spectrum of the pulse pair before and after the fiber for negative dispersion. Figure 1b shows the same spectra on an expanded 1 nm scale. The fringes are uniform and the phase shift can be easily deduced. The results were published[9].

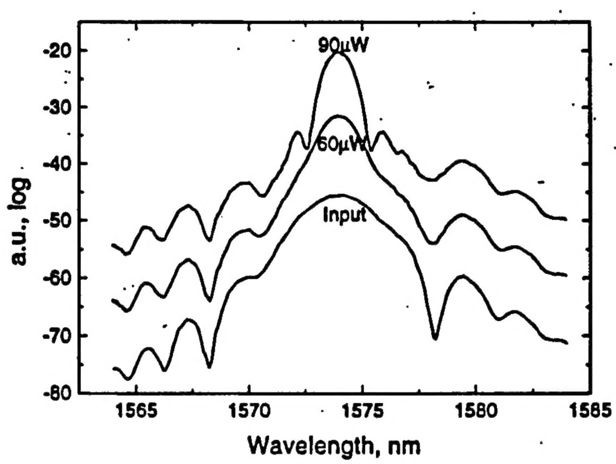

Figure 1a. Spectra before and after fiber, 20 nm span.

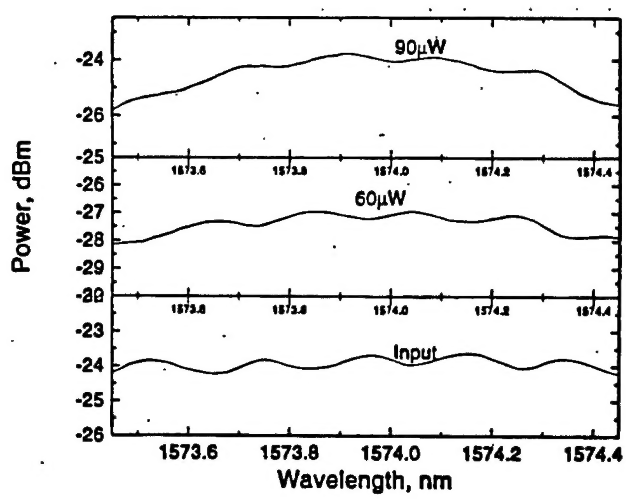

Figure 1b. Spectra before and after fiber, 1 nm span for different powers, negative dispersion loop mirrors.

Amplitude Squeezing of Solitons

There has been considerable interest in the amplitude noise reduction of solitons via nonlinear propagation and filtering as first demonstrated by S. R. Friberg et al. at NTT. Amplitude squeezing by itself has limited applications, since phase measurements with reduced shot noise require phase squeezing or squeezed vacuum with the proper phase shift. However, the phenomenon is of interest and prompted us to look into it both theoretically and experimentally. The theoretical approach we took differs from the one

used by other groups and leads to a rather simple interpretation of the phenomenon. A pulse is launched in a fiber with amplitude and width that does not satisfy the soliton condition. The pulse adjusts itself to become a soliton, shedding continuum in the process. The quantum noise accompanying the soliton and the continuum is correlated. In the evolution of the soliton and the continuum the noise evolves differently. Upon filtering and detection partial destructive interference can be produced by the continuum noise in phase with the soliton amplitude noise. This work has led to a publication[10] and a paper submission[11].

Quantum Theory of the Kerr Effect

If generation of squeezed radiation is to be achieved with propagation of a pulse through a fiber, it is necessary to understand the quantum mechanical description of the Kerr effect. Since the zero-point fluctuations extend over an infinite frequency range, a quantum description of a Kerr effect with an instantaneous response in a dispersion-free fiber leads to a kind of ultraviolet catastrophe since all frequencies can undergo four-wave mixing[12]. In fact, the origin of the singularity is not strictly of quantum origin. In the presence of white noise of unlimited bandwidth the same singularity is encountered. We have addressed the problem and shown that an analysis that linearizes the noise fluctuations does not encounter this singularity and gives a good description of the full quantum analysis for distances of propagation that produce 15 dB of squeezing or less. Another way of eliminating the singularity is to allow for the finite response time of the Kerr medium. This leads to coupling of the Kerr medium to a reservoir that introduces noise sources associated with the reservoir. The noninstantaneous response of the Kerr medium is, of course, associated with Raman gain. A self-consistent analysis has been developed to treat this problem[13]. This theory was followed by a full analytical solution of the problem[14]. The effect of Raman noise on squeezing deserved special attention, since it could be surmised that it would set a limit on the amount of squeezing achievable in its presence. This led to a theoretical investigation and experimental determination of the Raman noise to frequency offsets from the pump lower than ever measured before[15].

Fundamental Issues of Quantum Theory

The analysis of the generation of squeezed radiation calls for a self-consistent quantum analysis of nonlinear interactions. Nonlinear interactions are at the root of any measurement. Thus for example, if the intent is to measure the photon number in a pulse, the radiation is made to interact with a probe in a nonlinear Mach-Zehnder interferometer. The change of the probe phase is a measure of the photon number in the observed pulse. This problem is in close analogy to the squeezing process via the Kerr nonlinearity. If a self-consistent analysis exists for the latter, the measurement problem can be attacked by it as well. We have made considerable progress in analyzing the issues of the theory of quantum measurement[16,17]. The approach taken is to state that a quantum nondemolition (QND) measurement involves the interaction of the observable with a measurement apparatus that is itself described by quantum theory. Using this approach, one may follow the evolution of the wave function of the observable in the process of measurement. The wave function of the entire system, observable and apparatus, becomes entangled as the result of the measurement. If traced over the measurement

apparatus, the density matrix of the observable "collapses" into diagonal form[16]. This is consistent with, even though not congruent with, the von Neumann postulate that the act of measurement leads to a collapse of the wave function. Two QND measurements of photon number in cascade give the same value for the photon number in the second measurement as in the first[17]. This fact could be used by an "intelligent observer" to describe the evolution of the observable (photon number) in the second measurement by assuming that the first measurement projected the state of the observable into a photon eigenstate. This is a computational "trick" since, in fact, the state of the system remains throughout an entangled state of observable and apparatus.

The generation of squeezed radiation by a $\chi^{(3)}$ process is a quantum process that permits a semiclassical interpretation if the photon number of the pumps is large. In order to prove this we investigated the question under what circumstances the states generated by the squeezing process could violate Bell's inequality. We found that this would be the case only in the limit of a nonlinearity so large that the squeezing pulse would consist of a few photons[18].

Since QND measurements via the Kerr nonlinearity are a form of noise free amplification it could be expected that such measurements could help overcome the limits imposed by the nonunity quantum efficiency of photo detectors. This has been shown to be the case in the detection of twin beams in a theoretical paper[19].

References all of which acknowledge Grant

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Degrees and Appointments:

S. Namiki, received the PhD from Waseda University in 1997, on the basis of the work done at MIT.

Dr. F. X. Kärtner was appointed Professor at the University of Karsruhe, Germany, starting 1999.

J. K. Bounds, received SMEE degree in 1986.

C. R. Doerr, received PhD in 1994 and is member of Technical Staff at Lucent Technologies, Bell Laboratories

K. Bergman, received PhD in 1994 and is Assistant Professor at Princeton University.

L. Boivin, received PhD in 1996 and is member of Technical Staff at Lucent Technologies, Bell Laboratories.

Honors and Awards

Professor Haus

1994 Frederic Ives Medal of the Optical Society of America
1995 The President's 1995 National Science Medal
1997 Ludwig Wittgenstein-Preis Award of the Österreichische Forschungsgemeinschaft

Professor Ippen

1997 Arthur Schawlow Prize of the American Physical Society
1997 Quantum Electronics Award of IEEE/LEOS

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